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Distribution, vertical position and ecological implications of shallow gas in Bahía Blanca estuary (Argentina)

M.E. Bravo [a, *], S. Aliotta [a, b], S. Fiori [a, c], S. Ginsberg [a, d]

[a] Instituto Argentino de Oceanografía, CONICET, La Carrindanga Km 7, 8000, Bahía Blanca, Argentina
[b] Departamento de Geología, UNS, San Juan 672, 8000, Bahía Blanca, Argentina
[c] Departamento de Biología, Bioquímica y Farmacia, UNS, San Juan 672, 8000, Bahía Blanca, Argentina
[d] Departamento de Ingeniería Civil, UTN, FRBB, 11 de Abril 461, 8000, Bahía Blanca, Argentina

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A B S T R A C T

There has been a growing interest in the study of shallow gas due its importance in relation to the marine environment, climate change and human activities. In Bahía Blanca estuary, Argentina, shallow gas has a wide distribution. Acoustic turbidity and blanking are the main seismic evidence for the presence of shallow gas in the estuary. The former prevails in the inner sector of the estuary where gas is either near or in contact with the seabed. Gas deposits are generally associated with paleochannels corresponding to the Holocene paleodeltaic environment. Distribution studies of shallow gas in this estuary are necessary because its presence implies not only a geological risk for harbor activities but also because it may have noxious effects on the marine ecosystem, mainly on benthic communities. The comparison of benthic communities at a gas site (GS) with those at a control site (CS) indicated that gas could generate impoverishment in terms of individuals' abundance (GS: N = 357; CS: N = 724). Also, diversity indices showed great differences in the community structure at each site. This indicates that methane gas may act as a natural disturbance agent in estuarine ecosystems. The presence of gas in seabed sediments must therefore be taken into account when distribution studies are conducted of estuarine benthic communities.

1. Introduction

Shallow gas formation depends on evolutionary processes that occur in coastal depositional environments. Transgressive and regressive processes lead to dramatic changes in the distribution of organic matter (Weschenfelder et al., 2016) which, when trapped in sediments, is transformed into methane either via microbial degradation (biogenic origin) or thermal degradation (thermogenic origin, Floodgate and Judd, 1992). Methanogenesis is common in relatively modern continental shelves and its distribution covers ~30% of the world's coasts (Hovland and Judd, 1992; García-Gil, 2003). Archaea, the only microorganisms known to form methane (Rice, 1992), are strictly anaerobic and reduce carbon dioxide to methane using hydrogen, which competes with reducing-sulfate bacteria, the latter being better competitors (Rice, 1992). Therefore, methane gas deposits often contain hydrogen sulfide (Rice, 1992). When gas concentration exceeds methane solubility, bubbles are formed (García-Gil, 2003).

Research on shallow gas is of economic and environmental importance because it is a potential energy resource and a geological risk, and it has a key role in global climate change (Kvenvolden, 1999). It is known that gas affects the engineering features of sediments. For example, gas may blowout during drilling or natural gas escapes may either make —in extreme cases— structures collapse due to foundation undermining or simply reduce the cutting effort, preventing the settlement of engineering works (Davis, 1992). Therefore, shallow gas is a potential hazard for offshore petroleum exploitation. Additionally, in marine environments gas seeps may affect seawater chemistry, and if methane gas crosses the water column to reach the atmosphere, this may lead to the increase of greenhouse gases (Davis, 1992; Hovland and Judd, 1992; Emeis et al., 2004). Furthermore, because seabed fluid flow has a wide distribution, it becomes imperative to conduct research to understand marine biogeochemical cycles. Since the discovery of chemoautotrophic life-forms in 1977, it has been known that in places where deep-sea seeps occur there are organisms that live

* Corresponding author.
E-mail address: mebravo@iado-conicet.gob.ar (M.E. Bravo).

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only under the environmental conditions that these seeps provide (Judd and Hovland, 2009; Dando, 2010).

Studies on the effects of gas on benthic communities have been carried out only in areas of significant seepages at abyssal and intertidal depths (Dando et al., 1991a; Judd, 2003; Levin and Mendoza, 2007; Sellanes et al., 2008, 2010; Dando, 2010; Levin et al., 2010; Gracia et al., 2012; Jessen et al., 2011). In addition, the comparison of deep and shallow (those located at depths shorter than 200 m) seep sites revealed that the latter are the ones which have less, if any, gas obligate species and low biomass (Dando, 2010). However, it is worth noting that, compared to deep sites, shallow sites have received little attention. Among the few studies on shallow sites that could be mentioned are those conducted in Norway and England by Dando et al. (1994) and Judd et al. (2002), respectively, both of which revealed that physical changes occurred in the benthic habitat as a result of the formation of methane-derived carbonates. In these places, methane gas generates the presence of a hard substrate which, in turn, favors the settlement of sessile fauna, thus increasing local abundance and biomass (Dando et al., 1994). In England, gas seepage occurring in mudflats was found to have depreciable cementation effects on sediments and negligible effects on the intertidal fauna (Judd et al., 2002). Although several studies have focused on biogenic shallow gas distribution in bays, fjords and estuaries (Hill et al., 1992; Hovland and Judd, 1992; Karisiddaiah et al., 1992; Karisiddaiah and Veerayya, 1994; Wever et al., 1998; García-García et al., 1999a,b; Fleischer et al., 2001; Aliotta et al., 2002, 2006; 2011; Missiaen et al., 2002; García-Gil, 2003; Emeis et al., 2004; Lee et al., 2005; Orange et al., 2005; Iglesias and García-Gil, 2007; Laier and Jensen, 2007; Rollet et al., 2009; Sun et al., 2012; Weschenfelder et al., 2016), the effects of biogenic shallow gas deposits in contact with infaunal benthic organisms have never been considered as structuring agents in distribution studies on benthic communities.

Seismic surveys have confirmed the presence of shallow gas in different coastal systems all over the world (Karisiddaiah et al., 1992; Fleischer et al., 2001; Judd, 2003). Gassy sediments have been recorded along the South American Atlantic coast, particularly in Brazil and Argentina. In Brazil, shallow gas has been found in: Patos Lagoon, Guanabara Bay, the shallow parts of Amazonas Continental Shelf and Campos Basin (Weschenfelder et al., 2016). In Argentina, gas deposits have been reported in: La Plata River estuary (Parker and Paterlini, 1990), San Matías Gulf (Aliotta et al., 2000), the Beagle Channel (Bujalesky et al., 2004), and Bahía Blanca estuary (Aliotta et al., 2002). Gas reservoirs are widely distributed in Bahía Blanca estuary and are either close or in contact with the seabed, mainly in the inner zone of the estuary (Aliotta et al., 2002, 2006; 2011) where the presence of this hydrocarbon is recorded particularly in a large area of the port sector (Aliotta et al., 2011).

Gas origin is related to transgressive-regressive processes that occurred in the Holocene (Aliotta et al., 2006; Giagante et al., 2008). Distribution studies on subtidal benthos at the soft bottom of Argentine estuaries have been focused on the following environmental variables: grain size, salinity, and organic matter (Elías, 1992; Bremec, 1989, 1990; Elías and Ieno, 1993; Elías and Bremec, 1994; Giberto et al., 2004, 2007). Although the presence of gas deposits in Argentina has been recorded since the 90′s (Parker and Paterlini, 1990), no studies have been carried out since then on the effects of gassy sediments on benthic organisms.

In view of the above, the purpose of the present study was to determine gas distribution as well as its vertical arrangement at the sea sub bottom in the inner sector Bahía Blanca estuary. To this end, and taking gas distribution into account, the macroinvertebrate benthic communities at a gas site (GS) were compared with those at a control site (CS). The results collected will allow us to evaluate the effects of methane gas on marine benthic communities.

1.1. Study area

Bahía Blanca estuary (BBE) is located in the South-West of Buenos Aires Province, Argentina (Fig. 1). It belongs to the northern sector of a large and complex system composed of islands and channels of different sizes. Because this complex system of islands and channels to which BBE belongs is of great value for the conservation of biodiversity, 85% (250.000 ha) of the total area of this system is under legal protection by means of four reserves. In spite of this legal protection, BBE is exposed to strong anthropogenic pressure from activities related to agriculture, petrochemical and urban centers, and the main deep-water port of Argentina. The major anthropogenic disturbances caused by these activities are dredging, input of marine invasive species, and contamination by industrial effluents, such as untreated urban sewage.

BBE is formed of extensive mudflats with one large sinuous main channel known as the Principal channel whose water depth is maintained at 15 m by dredging to ensure the passage of ships to ports. The southern sector of the Principal channel is formed by a large intertidal area with very sinuous or meandering interconnected tidal channels of different sizes and with a general NW-SE orientation (Ginsberg and Aliotta, 2011). The tidal regime of the estuary is semidiurnal with mean amplitude of 2 m at the mouth and more than 4 m at its head (Perillo. 2004). The Principal channel has tidal currents reversible with mean velocities of 1 m s^{-1} and 1.4 m s^{-1} for flood and ebb, respectively (Ginsberg and Aliotta, 2011). BBE has minor freshwater contributors that are responsible for the formation of spots characterized by low salinity but with prevailing marine conditions. The Sauce Chico River, with a mean discharge of 150,000 m^3/day and the Napostá Grande stream, with a mean discharge of 91,000 m^3/day, are the major contributors to the freshwater superficial drainage net (Limbozzi and Leitao, 2008). Additionally, BBE receives other freshwater inputs through continental runoff, sewage discharges and harbor-related operations (La Colla et al., 2015). Mean salinity values vary between 32.83 and 33.98 psμ in the inner zone of the estuary (Freije and Marcovecchio, 2004).

The geomorphological features of BBE are the result of transgressive-regressive processes that occurred during the Holocene (Aliotta and Lizasoain, 2004; Aliotta et al., 2013). These processes generated coastline migration evidenced through the presence of conchilliferous sand strands parallel to the coast. These sand strands evidence a sea level 7 m above the current sea level (Aliotta and Farinati, 1990; Farinati and Aliotta, 1997; Aliotta et al., 2003, 2006; Aliotta and Ginsberg. 2008; Spagnuolo et al., 2006). The area currently occupied by the estuary was a fluvial delta prior to postglacial transgression. Previous studies were performed on the evolutionary characteristics of the deltaic environment, particularly in the southwestern sector of BBE (Aliotta et al., 1999; Spalletti and Isla, 2003; Giagante et al., 2008). Additionally, paleochannels were found both in BBE (Aliotta et al., 2004; Spagnuolo et al., 2006; Giagante et al., 2008, 2011) and the continental shelf (Aliotta et al., 1999, 2011).

In general, the sandy fraction is dominant in the outer zone of BBE whereas the fine fraction (clay and silt) predominates in the inner zone, mainly in tidal flats (Gelós et al., 2004). The presence of three bottom-types was recorded in the subtidal area of the estuary (Lizasoain, 2007). The first two were found to be formed of relatively compacted sediments. One of them, Pampean Formation, which is of Pleistocene origin, was observed to be either highly compacted or cemented whereas the second bottom-type, which was found to be less cohesive, is related to a palaeodeltaic

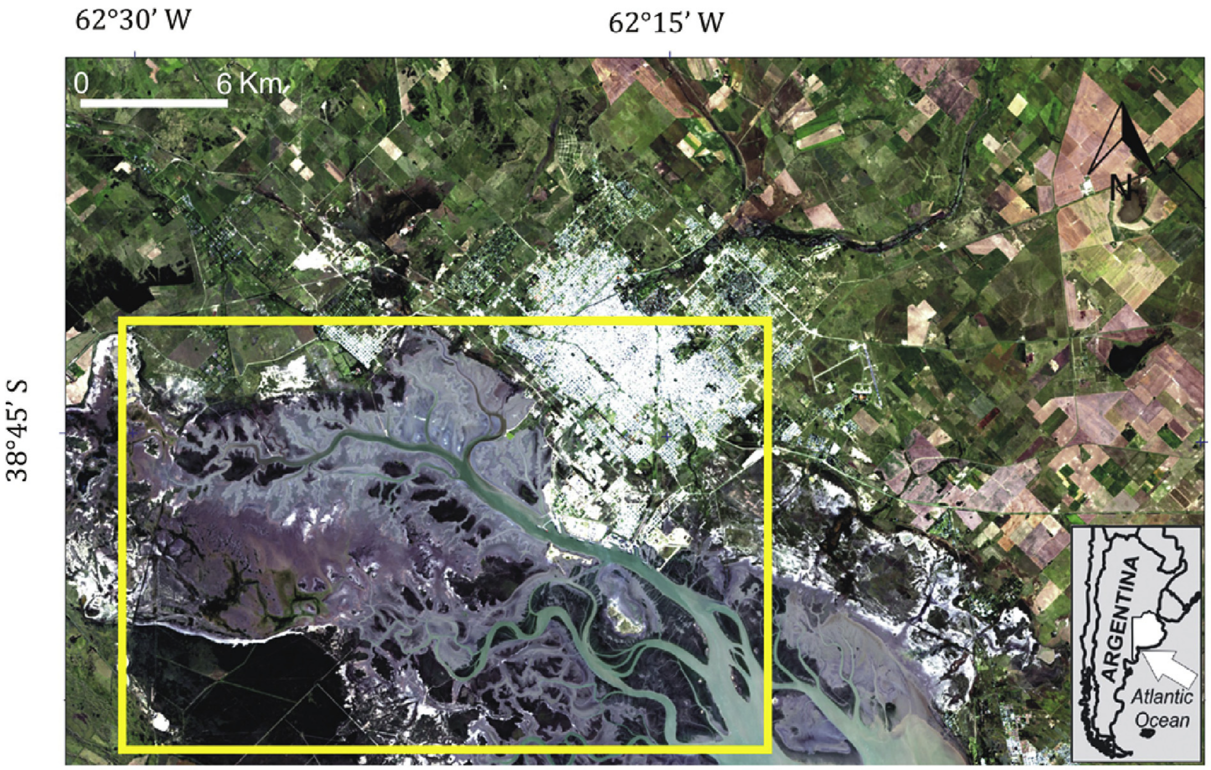

Fig. 1. Map of the inner zone of the Bahía Blanca Estuary (Southwestern Atlantic, Argentina) showing the location of the study area (yellow box) for shallow gas distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

environment from Holocene. The third bottom-type, which is the dominant one and forms a relatively large dune field in the outer zone of the estuary, was observed to be composed of sand (Aliotta et al., 1987; Lizasoain, 2007; Minor Salvatierra et al., 2015). In general, the hard bottom is restricted to the dredging sector of the main channel, the deepest areas and some erosive flanks of the channels (Lizasoain, 2007).

Although the information available on the benthic macrofauna of BBE is not only isolated but also sporadic, several surveys were carried out between 1981 and 1983 to describe the spatial structure of intertidal and subtidal communities of soft substrates (Elías, 1992, 1995; Elías and Ieno, 1993). These studies not only identified 69 species but also demonstrated that polychaetes are dominant in both abundance and number of species.

2. Materials and methods

For shallow gas mapping, seismo-acoustic prospection was carried out on board the ship “Buen Día Señor” which belongs to the Instituto Argentino de Oceanografía (IADO). During navigation, a base map containing navigation charts of the Argentine Naval Hydrographic Service was used. A differential globe positioning system (DGPS) connected to navigation software was used to control position data in real time. Seismic prospection of the marine subbottom was carried out using high-resolution seismic profiling operating with a frequency of 3.5 kHz. Data were collected and processed using specific software.

Considering the information available on shallow gas distribution (Fig. 2), two sampling sites (Fig. 3), GS and CS, both with similar geological features (depth and geomorphology), were selected. Particularly, in this sector seismic records were carried out: five longitudinal and 11 transversals to the channel – to obtain a high density of data, enabling a detailed mapping of shallow gas in the sub bottom. Samples were collected along a transect whose direction coincides with a seismic record, both being parallel to the southern veril of the Principal channel. In order to establish sedimentological features of the seabed, at each study site, three sediment samples were collected using a snapper. Sediment texture was analyzed macroscopically and using laser diffractometry (Mastersizer, 2000 Malvern Instruments, UK). Total organic matter content from each sample was obtained by calcination. A paired *t*-test was performed to compare organic matter content at the two sites considered. Sampling of benthic organisms was conducted using a dredge (10×30 cm frame, 0.5 mm mesh) for 1 min at 2 knots of speed at GS and CS. Samples were sieved on board the ship with a 0.5 mm mesh, they were preserved in 4% formaldehyde and analyzed at the laboratory. Organisms were identified using the literature available on the area (Ringuelet, 1966, 1969; Fauchald, 1977; Orensanz, 1973, 1974; Lichstein de Bastida and Bastida, 1980; Boschi et al., 1992; García-Madrigal, 2007) and further quantified. When a specimen could not be identified to species level in spite of the clear morphological differences among individuals of the same genus, family or even higher taxonomical level, it was defined as a specific morphospecies. Total biomass was measured by wet weight with milligram precision. In order to describe the community associated to the two sampling sites considered, the following richness and diversity indices were estimated: Margaleff (d), Shannon-Wiener (H′), Pielou (J′) and Simpson (λ). The quantitative data index Czekanovski-Dice-Sorensen was also estimated. The relative abundance and biomass (in percentage) of higher taxa at GS and CS were also compared.

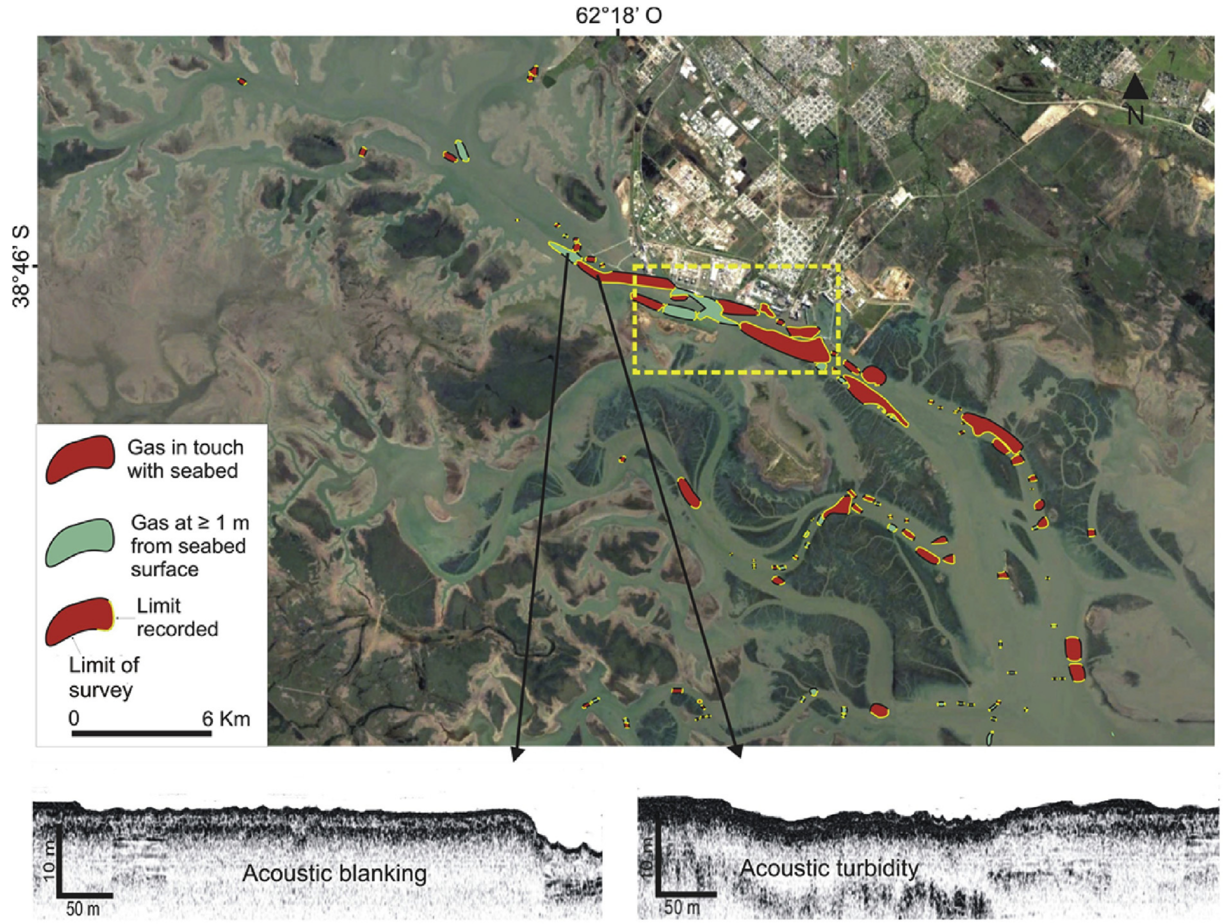

Fig. 2. Map of shallow gas distribution in the inner zone of Bahía Blanca Estuary. The gas deposits are classified on the basis of their distance to the seabed: "surface" (red) and "sub bottom" (green). Different seismic evidences founded in this study are shown below the map. The arrows indicate the acoustic blanking seismic evidence correspondence to sub bottom gas, and acoustic turbidity associated to surface gas. The yellow box represents the location of the sampling sites (detailed in Fig. 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Results and discussion

In the last decades, subtidal habitat mapping has become of growing interest because of its potential use as a management tool in conservation programs. Geophysical techniques are useful for the characterization and classification of subtidal habitats at large scales (Kostylev et al., 2001; Roff et al., 2003; Herkül et al., 2017). Although shallow gas distribution worldwide has been thoroughly studied (Hovland and Judd, 1992; Karisiddaiah et al., 1992; Fleischer et al., 2001; Aliotta et al., 2002, 2006; 2011; García-Gil, 2003; Emeis et al., 2004; Weschenfelder et al., 2016), only a few studies have been carried out to date on its effects on benthic organisms (Dando, 1991a,b; Judd et al., 2002; Judd and Hovland, 2009).

3.1. Gas distribution and types of evidences in seismic records

Anomalous acoustic responses in seismic data allowed us to map gassy sediment distribution in BBE (Fig. 2). Based on the distance between gas deposits and the seabed surface, shallow gas was classified into two categories: "surface" and "subbottom" and was also mapped. The surface category indicated gas accumulations located 1 m or less from the seabed, whereas the subbottom category indicated accumulations located at a distance longer than 1 m below the seabed. Gas reservoirs are widely distributed in the estuary and are either close or almost in contact with the seabed in the inner zone. In the latter, hydrocarbon occupies a wide area of the marine subbottom including the maritime front where petrochemical industries and White-Galván port complex are located. The presence of gas in the seismic record was evidenced as a total or partial masking effect of the reflectors forming the column of subbottom sediments as a result of the fact that the seismic signal was attenuated in the sediments carrying gas bubbles (Fig. 2). This effect is known as acoustic turbidity (García-García et al., 1999a,b). Seismic records also evidenced, in the form of acoustic turbidity, the presence of surficial gas deposits longer than 1.5 km in the port area, either near or in contact with the seabed.

Acoustic blanking was another evidence of gas accumulations in the estuary (Fig. 2). In this kind of anomaly, the roof of gas deposits adopts the form of a very strong reflector and therefore the underlying seismic record is masked to the extent that the source of gas cannot be detected (García-García et al., 1999a,b). Acoustic blanking was detected all over the estuary, the wider deposits – mapped by Aliotta et al. (2009, 2011) – being located in the outer area. These subbottom gas accumulations evidenced as acoustic blanking occupy deposits of variable sizes, the maximum size reaching 600 m or more. Relative distance between gas deposits and seabed varies from 2 to 12 m. These gas deposits are in general associated with paleochannels in the outer zone and with channel veriles both in the inner and in the outer zones (Giagante et al., 2008; Aliotta et al., 2009, 2011).

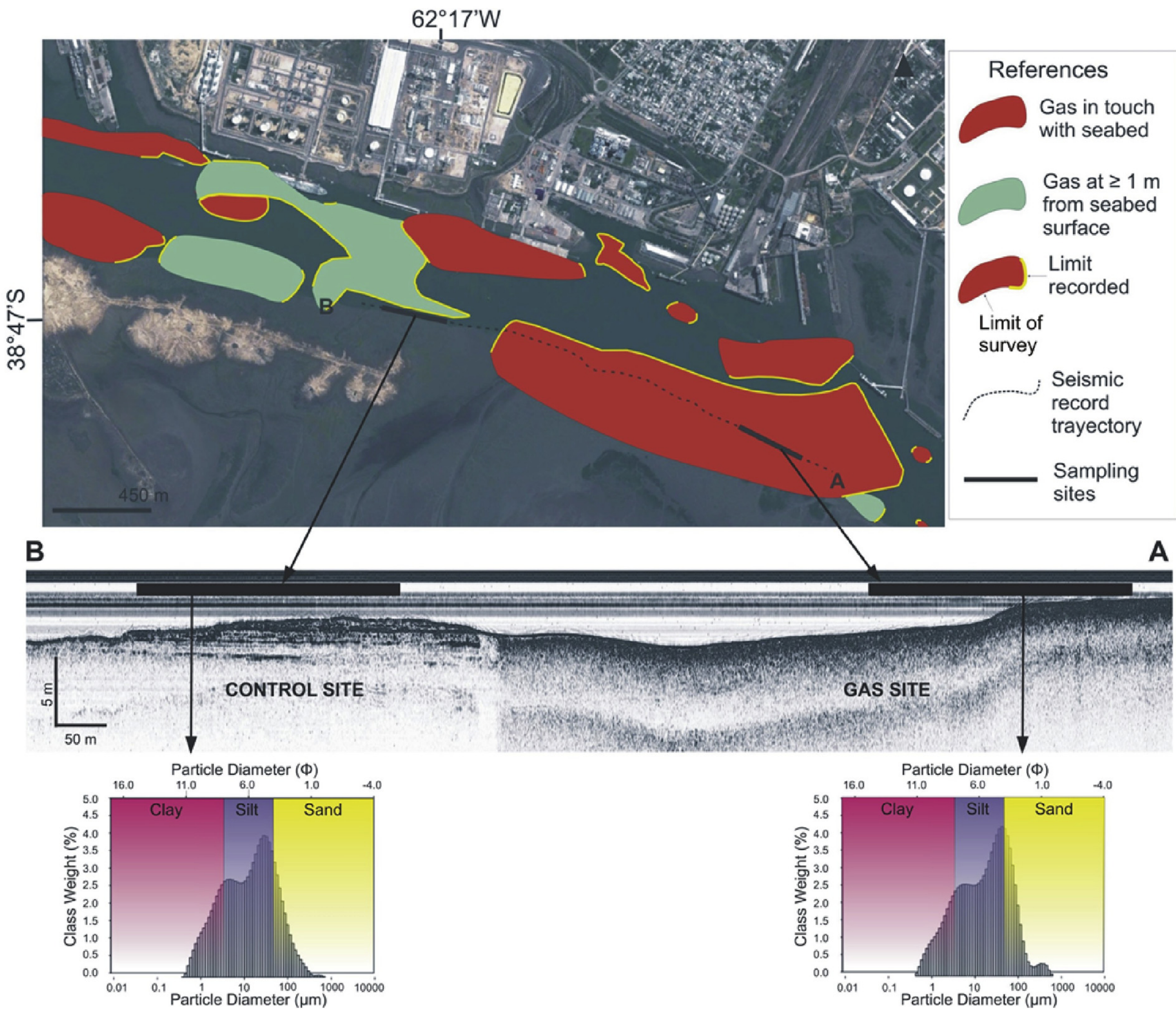

Fig. 3. Detail of the location of the sampling sites with the seismic evidence of presence and absence of shallow gas. Below the seismic record are represented the frequencies distribution of sediments in each site.

Aliotta et al. (2002) described for first time the presence of several sectors with shallow gas (mainly methane) in the seabed of BBE. Gas deposits were formed during sea level rise that occurred at the beginning of the Holocene and which generated the burial of continental organic matter by clayey silt transgressive sediments (Aliotta et al., 2009).

Gas deposits are, in general, associated with areas of low palaeotopography and, in some cases, with sigmoidal progradation seismic configuration along a surface of erosive discontinuity (Aliotta et al., 2002, 2009). Sigmoidal progradation seismic configuration is associated with paleovalleys and paleochannels that form the deltaic palaeoenvironment developed during late Pleistocene-early Holocene (Aliotta et al., 1999; Giagante et al., 2008), before the last marine ingression. The gradual increase in sea level during the Holocene caused the burial of continental organic matter by marine sediments. Methanogenic archaea-mediated carbon degradation under anoxic conditions gives rise to methane gas formation, while sedimentary facies control gas migration. The latter form the roof of gas deposits, which is evidenced as a false reflector on the seismic profiles partially masking the underlying stratification (Aliotta et al., 2009). Shallow gas association to paleodrainage channels was also observed in Chesapeake Bay where shallow gas was found to be in contact with the seafloor (Hill et al., 1992).

It is interesting to analyze the relationship between the distribution of the seismic evidences of shallow gas and the texture of the surficial sediment distribution on the seabed of BBE. Dominance of acoustic turbidity in the inner zone of the estuary coincides with dominance of clayey sediments. This agrees with the model proposed by Judd and Hovland (1992) and with data collected in Ría Muros-Noia by Magariñoz-Álvarez et al. (2002) who found acoustic blanking associated with clayey sediments, which, in turn, coincides with the sediment composition of sequence S3 reported in the inner area of the estuary (Giagante et al., 2008). Sequence S3 is characterized by the presence of paleochannels that frequently have gas deposits (Fig. 4, Giagante et al., 2008). Evidence of acoustic turbidity has been recorded in sediments at gas concentrations lower than 1% (Judd and Hovland, 1992) whereas acoustic blanking evidence is related to larger gas concentrations in sediments (Magariñoz-Álvarez et al., 2002).

The most important controlling factor of gas accumulation, both in lateral and vertical sense, is stratigraphy (Magariñoz-Álvarez et al., 2002; Weschenfelder et al., 2016). The seismic stratigraphic column in the inner zone of BBE estuary is characterized by five Late Pleistocene-Holocene seismic sequences (Aliotta et al., 2014), which have been described following the order of their

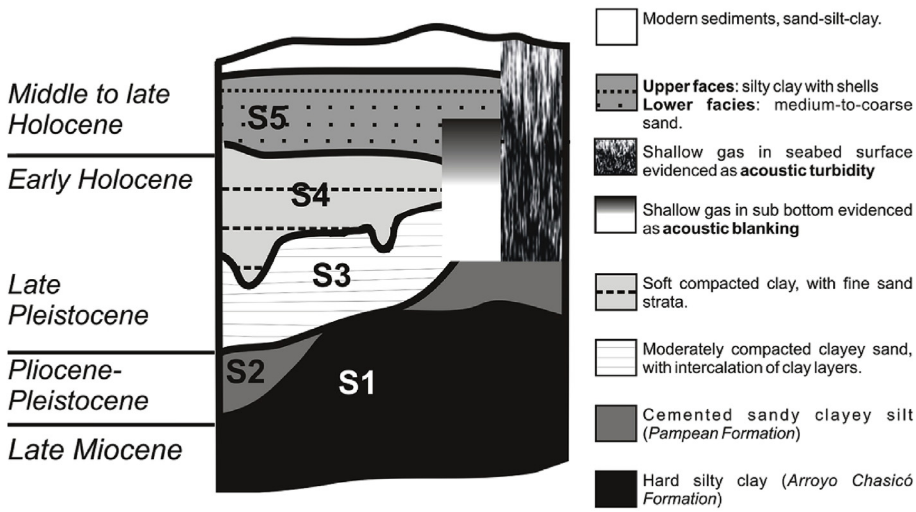

Fig. 4. Schematic representation of the seismostratigraphic features of sub bottom from the study area. Modified from Aliotta et al., (2014).

stratigraphic position. All the seismic sequences and their lithological and seismic features are summarized in Fig. 4. Shallow gas was found in sequence S5 and originated from sequence S3. Perforation data suggest that gassy sediments are composed of gray fine sandy silt and are loosely packed (Aliotta et al., 2009).

Shallow gas deposits are frequently associated to carbonate cement precipitation and local sediment lithification. The formation of methane-derived carbonate was observed in Denmark (Jensen et al., 1992; Jorgensen, 1992) at depths similar to those at which our study was carried out. The process occurs both for oxic and anoxic microbial oxidation of methane which increases alkalinity, leading to exceptionally high pCO_2 of interstitial water of gas-charged sediments and this could result in carbonate precipitation (Jorgensen, 1992). In Denmark, gas sediments are therefore characterized by the presence of hard substrata while in our study sites carbonate precipitation was not observed to occur and soft sediments were found to have less cohesiveness due to the presence of gas bubbles. This had been hypothesized by Hill et al. (1992) who argued that the low cohesiveness of gas-charged sediments makes them more susceptible to resuspension and slumping. The only hard substrata found in our study were rounded rock fragments that belong to the Pampiana formation (Pleistocene). The absence of seeps and the different nature of sediments in our study area seem to be responsible for the absence of gassy sediment lithification.

Although cohesiveness was observed to be lower in sediments at GS than in those at CS, the sedimentological analysis indicated no granulometric differences between the two sites, total mean at both sites being 6 phi. At GS, mean value varied between 5.3 phi and 6.7 phi while at CS it varied between 5.9 phi and 6.3 phi. Sediments from both GS and CS therefore belong to the textural group of sandy mud granulometrically composed of very fine sand and coarse silt. Although organic matter showed no significant differences between GS and CS ($t = 2.04$, $p = .178$), it was higher at GS than at CS with median values of 4.52% and 3.4%, respectively.

3.2. Benthic communities

A total of 48 taxa was identified at both study sites (Table 1), with a different representation at each site ($Cz = 0.52$, Table 2). Total abundance of organisms was lower at GS (357 individuals) than at CS (724 individuals). Diversity and evenness were higher at GS than at CS (Table 3). The most abundant and common species at GS was the polychaete *Aricidea* sp. which represented 66.7% of total abundance. At CS, the amphipod *Monocorophium insidiosum* was the dominant species and represented 72% of total abundance. The comparisons of relative abundance and biomass of phyla taxonomic level (Fig. 5) showed that at GS annelids and cnidarians were dominant in abundance and biomass respectively, while at CS arthropods were dominant in abundance and annelids were dominant in biomass. Total biomass was higher at GS than at CS mainly as a result of the contribution of the cnidarian *Stylatula darwini* that was absent at CS. This cnidarian was found at intertidal and shallow subtidal of the GS and was absent at CS. Although distribution studies of *S. darwini* have been carried out (Bremec, 1990; da Silva and de Castro, 2011), no research has been conducted to date on gas deposits positively associated with the presence of this species.

Shallow gas appears to affect abundance, composition and distribution of benthic species in BBE. In general, the benthic community at GS was dominated by polychaeta followed by crustaceans whereas at CS this relationship was reversed. This could be due to a differential sensitivity of benthic organisms to the presence of gas in sediments. Previous studies attributed the macrobenthic community structure to organic matter enrichment as a result of sewage discharges even at sites distant from these disturbing sources (Elías, 1987). Based on findings from our study, higher organic matter content at gas sites appears to be more related to methane than to sewage effluents. This has not yet been taken into account in studies of distribution of benthic communities.

The presence of fine sediments with high organic matter concentrations has been associated with seabed currents of low intensity (Sanders, 1958). Taking into account the fauna-sediment relation in our study area, and because sediments were characterized as sandy muds, deposit feeders were expected to be the dominant group (Sanders, 1958; Fauchald and Jumars, 1979; Rhoads and Germano, 1982). Whereas GS was found to be formed of suspension feeders, carnivores and scavengers followed by surface deposit feeders, at CS deposit feeders were observed to be the dominant feeding guild (Fauchald and Jumars, 1979). At GS, the paraonidae *Aricidea* sp. was found to be dominant in abundance and its feeding guild was observed to be variable between species from deposit feeder and carnivore to suspension feeder (Fauchald and Jumars, 1979). In contrast, the detritivore *Monocorophium insidiosum* (Guerra-García et al., 2014) was found to be dominant at CS which evidenced the lowest organic matter content. Gas

Table 1
Table of presence (symbolized as X) versus absence of benthic species identified in each study site, Gas Site (GS) and Control Site (CS).

Taxa		GS	CS
Cnidaria			
	Stylatula darwini	X	
	Obelia spp.	X	
Mollusca			
	Pitar rostratus	X	X
	Ostrea sp.		X
Echinodermata			
	Ophioplocus januarii	X	
Crustacea			
	Pagurus criniticornis	X	X
	Cyrtograpsus altimanus		X
	Neomysis americana	X	
	Arthromysis magellanica	X	X
	Caprellidae undet		X
	Phoxocephalidae undet.	X	
	Monocorophium insidiosum	X	X
	Ostracoda undet.	X	
Pycnogonida			
	Anoplodactylus sp.		X
Annelida			
	Aricidea sp.	X	X
	Paraonidae undet. 1	X	
	Glycera americana	X	
	Terebellides totae	X	
	Leodamas verax	X	X
	Polydora cornuta	X	X
	Malacoceros sp.	X	
	Laeonereis acuta	X	
	Eteone sp.	X	X
	Chone sp.		X
	Halosydna patagonica		X
	Harmothoinae undet.		X
	Eusyllinae undet.	X	X
	Syllis sp.	X	
	Nereididae undet.	X	X
	Melinna uruguayi	X	X
	Nothria setosa		X
	Terebella plagiostoma		X
	Aphelochaeta sp.	X	X
	Lumbrineris tetraura		X
	Lumbrineriopsis mucronata		X
	Lumbrineridae undet.	X	X
Nematoda			
	Nematoda undet.	X	X
Undetermined			
	Phylum undet. 1		X
	Phylum undet. 2	X	
Bryozoa			
	Scruparia ambigua	X	
	Bugula neritina	X	
	Bugula stolonifera	X	X
	Crisia sp.	X	X
	Conopeum sp.		X
	Briozoa undet. 1	X	X
	Briozoa undet. 2		X
	Bowebankia imbricata	X	
Ciliophora			
	Folliculina sp.		X

presence therefore affects the ecological functions of the benthic environment, altering the trophic structure of the environment.

Gas seepages generate changes in the seabed topography and cause sediment sorting and lithification, thus affecting the faunal composition of the area (Dando and Hovland, 1992). No other previous studies carried out at shallow depths, except ours, have reported shallow gas variability. Although Dando et al. (1994) study performed in Denmark and Judd et al. (2002) study performed in England were both carried out at shallow depths, they are hardly comparable with ours because they were conducted in beach and intertidal environments with gas seepages and methane-derived carbonate cementation. Most of the studies on the benthic effects of gassy sediments report enrichment in diversity as a result of the presence of hard sediments (Dando and Hovland, 1992; Jensen et al., 1992; Dando et al., 1994) or a benthic methane-dependent fauna (Dando et al., 1991a; Luth et al., 1999). However, in gas seepages from an intertidal area of Torry Bay, Judd et al. (2002) observed that seepages seem to have no effects on faunal composition and diversity. The absence of patterns of differentiation in benthic communities in gas sediments was also reported in a shallow gas field from the Gulf of Cádiz (Rueda et al., 2012). On the other hand, impoverishment in terms of diversity was observed in methane-bearing sediments (Dando et al., 1991a,b; Levin, 2005). In spite of the differences between the above-mentioned studies and ours, Judd et al. (2002) also found low numbers of a Corophidae amphipod at the gas site and this could be due to the sensitivity of the amphipod to sulphide-rich sediments (Meadows et al., 1981). Although hydrogen sulphide concentration was not measured in our study, this gas is associated with shallow gas deposits (Judd, 2004) and it could thus be assumed that it inhibits

Table 2
Individual abundance and biomass per species in each study site. Abundance is expressed in terms of individuals by trawling, and biomass is in grams.

Taxa	Abundance		Biomass	
	GS	CS	GS	CS
Stylatula darwini	4	0	16.232	0.000
Pitar rostratus	1	2	8.392	0.905
Ostrea sp.	0	1	0.000	0.000
Ophioplocus januarii	1	0	0.476	0.000
Pagurus criniticornis	1	4	0.010	0.098
Cyrtograpsus altimanus	0	3	0.000	0.379
Neomysis americana	1	0	0.022	0.000
Arthromysis magellanica	5	4	0.140	0.048
Caprellidae undet	0	4	0.000	0.035
Phoxocephalidae undet.	6	0	0.009	0.000
Monocorophium insidiosum	36	519	0.015	0.134
Ostracoda undet.	1	0	0.000	0.000
Anoplodactylus sp.	0	1	0.000	0.002
Aricidea sp.	236	25	0.015	0.010
Paraonidae undet. 1	2	0	0.007	0.000
Glycera americana	1	0	0.199	0.000
Terebellides totae	1	0	0.197	0.000
Leodamas verax	2	12	0.100	0.344
Polydora cornuta	20	18	0.149	0.004
Malacoceros sp.	3	0	0.129	0.000
Laeonereis acuta	1	0	0.003	0.000
Eteone sp.	4	53	0.000	0.02
Chone sp.	0	3	0.000	0.063
Halosydna patagonica	0	1	0.000	0.14
Harmothoinae undet.	0	2	0.000	0.011
Eusyllinae undet.	1	4	0.004	0.009
Syllis sp.	1	0	0.000	0.000
Nereididae undet.	2	1	0.002	0.000
Melinna uruguayi	4	41	0.004	0.146
Kimbergonuphis tenuis	0	2	0.000	0.005
Telepus plagiostoma	0	1	0.000	0.035
Aphelochaeta sp.	11	10	0.033	0.003
Lumbrineris tetraura	0	5	0.000	0.025
Lumbrineriopsis mucronata	0	5	0.000	0.389
Lumbrineridae undet.	1	1	0.000	0.000

Table 3
Quantitative diversity indicates for each study site. S:species richness, N:total abundance, d:margalef richness, J:Pielou's evenness, H′(loge):Sannon-wiener index, λ:Simpson index.

Sample	S	N	d	J′	H′(loge)	λ
GS	26	357	4253	0,4563	1487	0,4514
CS	26	724	3797	0,3924	1278	0,5243

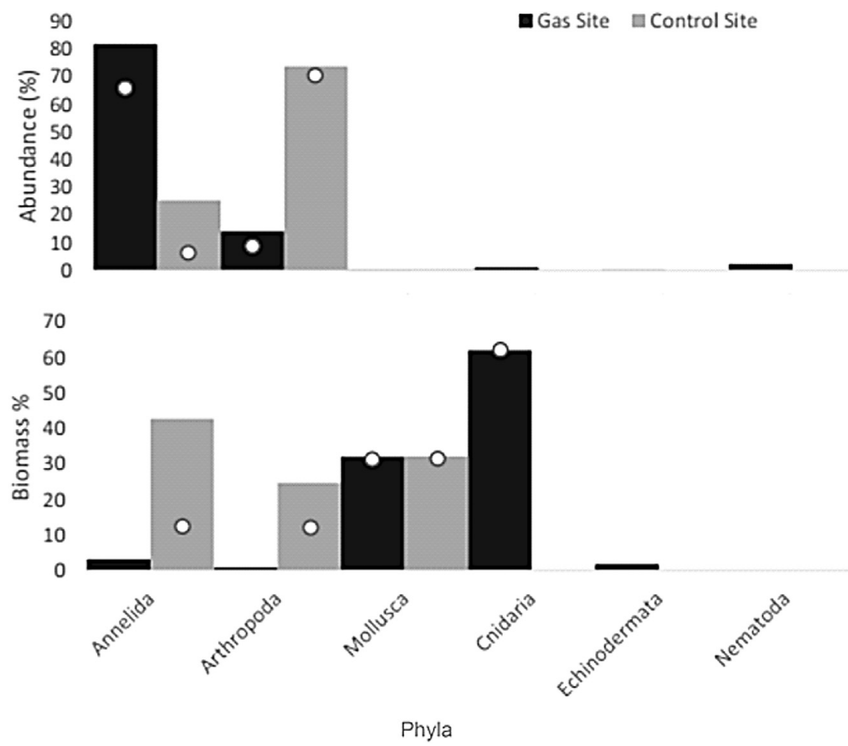

Fig. 5. Relative abundance and biomass of benthic macro-invertebrate phyla in each study site (Gas Site and Control Site). The white circles represent the relative contribution of dominant species (when higher than 5%) into each phylum (see Table 2).

Monocorophium insidiosum.

In ecological terms, it is possible to clearly identify the benthic communities of each site because their structures are different. The diversity index showed that dominance was higher at CS than at GS. In addition, although no differences were recorded between the number of species at GS and that at CS, the markedly lower abundance at GS suggests that methane produces a negative effect on organisms, thus affecting the composition of subtidal benthos in BBE. Furthermore, the presence of gas bubbles in sediments generates less cohesiveness (Hill et al., 1992), which could be a physical restriction for the settlement of infaunal benthic organisms. In relation to this, Hill et al. (1992) proposed that gas-charged sediments are a poor substrate and a poor habitat for the settlement of both sessile organisms and burrowing organisms. According to this, field naked-eye analysis revealed that gassy sediments showed less cohesiveness than the sediments at the CS although at both sites granulometry was equal (sandy mud). The physical effects of gas on sediments could be compared with those derived from bioturbation generated by high densities of deposit-feeders (Levinton, 1995). In both cases, the characteristics of the sediments impede the settlement and survival of some functional groups that are poorly equipped to survive under unstable conditions of watery sediments. Thus, shallow gas on the seabed surface may behave as an important modelling factor for the benthic habitat, making it therefore necessary to take shallow gas distribution into account when benthic community mapping is done.

4. Conclusions

Gas sediment distribution mapping was done based on the anomalous acoustic responses in seismic data collected from BBE. Gas is known to be widely distributed in the estuary, in contact with the seabed in the inner zone and near the seabed in the outer zone. Acoustic turbidity is the dominant evidence type from the inner zone. Within the port area, gas is in contact with the seabed, forming large deposits. Taken together, the data collected from the present study lead to the conclusion that the presence of gas i) influences subtidal benthic macroinvertebrates, ii) generates a marked difference in community structure, and iii) diminishes total individual abundance. Therefore, and taking into account that gas deposits not only affect the habitat quality of infaunal organisms but also modify benthic community structure, it becomes mandatory to further learn about shallow gas distribution. The fact that the seabed sediment type is the same in GS and CS (sandy mud) excludes the seabed material as a variable determining differences found in the benthic communities. Methane gas in sediments may act as a carbon source or as a noxious agent for life. Diversity impoverishment at GS could be due to the degree of sensitivity of some species to methane gas as in the case of *Monocorophium insidiosum*. Further studies on the influence of gas on benthic invertebrates must include measurements of methane gas concentrations, ecotoxicological experiments and/or stable isotope analysis. Our future studies will include quantitative analysis of methane gas in sediments. As gas deposits behave as an important modelling factor of habitat, their presence may affect the ecological functions, structure and distribution of benthic communities. In view of this, it becomes imperative to take shallow gas distribution into account when benthic community mapping is done.

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